1998

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ABSTRACT

A software tool-set, from which dynamic simulation of any type of positive displacement compressor can be constructed, is developed using an object oriented approach. This approach has three major advantages. The first is that a simulation code for any type of positive displacement compressor can be developed quickly with a uniform protocol. The second advantage is the ease of handling of creation, annihilation, merger and separation of compression chambers, and the changes in topology associated with them. These events are common to most types of compressors, except for the simplest reciprocal piston type. The third advantage is the ease of replacing the models of components, such as the valves or even the compression chambers themselves, as different designs or better models become available.

The simulation codes are used in optimizing the design parameter of compressors being developed, as well as competitive analysis of different types of compressors that would be deployed under the same service requirements.

1. INTRODUCTION

The use of simulation as a design evaluation tool has been common practice for a wide variety of types of positive displacement compressors[1-3]. The majority of simulation codes for engineering use in general, and compressor simulation in particular, is still written in a procedural language such as FORTRAN, and each code is typically designated for a particular type of compressor. In order to analyze different types of compressors, numerous codes must be developed in redundancy.

The use of an Object Oriented Language such as C++ provides a number of advantages over procedural languages. The first is that the codes for different types of compressors can be developed from a single tool-set. The development of physical model , based on thermodynamics for the compression chambers or fluid mechanics for valves and other passages, needs to be done once during the development of the base class objects. All the models of a chamber of a specific type of compressor inherit the properties of the thermodynamic modeling, while manifesting specific characteristics of the compressor type such as the relationship between the angular position and the chamber volume.

The second advantage is the ease of creation and annihilation of objects. This allows for greatly simplified simulations of compressors involving the creation, annihilation and merger of the chambers, such as rotary vane and scroll compressors. Once the objects are set in motion, the objects themselves will take care of their own creation, annihilation and merger.

The third advantage is the very canonical way a compressor model can be constructed. Once the objects pertinent to a particular type of compressor are identified, the simulation code can be written by declaring the components and properly connecting them. The objects that are common to many compressors, such as the valves, can be used repeatedly without re-writing or re-compiling in most cases. The object that is specific can be constructed through a minimal enhancement to a base class object that already exists.

Through these advantages, the model of a compressor is essentially constructed by "assembling and connecting" these parts, specifying when the events such as creation are to take place, and then starting the clock. This allows very easy alteration of the code. For example, one could very easily improve the modeling of components or to reflect design changes that affect the connectivity of the components. These advantages allow very rapid development of dynamic simulation codes as is demonstrated in the following sections.

2. BASE CLASS OBJECTS

The objects described here are present in all positive displacement compressors. Some objects, such as valve and leak are used in simulations without additional enhancement. Others, such as generalized compression chamber, serve as a base class object from which a specific type of compression chamber pertaining to a specific type of compressor can be derived.

2.1 Generalized Chambers

A chamber is characterized by the volume (as a function of the position), mass of the refrigerant contained in the chamber, and the state of the refrigerant. The chamber object not only contains these information, but also calculates its own volume from a given formula or a table, computes refrigerant mass and refrigerant state based on the conservation of mass and the first law, and handles merger and separation with other chambers. All the objects derived from this base class will inherit these features.

2.1.1 Compression Chamber

The compression chamber object is a special case of chamber where the volume is given as a specific function of position, the form of which varies from compressor to compressor. The state of the chamber is computed using the first law of thermodynamics.

Alternatively, a modified form of the first law can be used to economize the computation time. The latter is derived based on the assumption that the dominant process of the chamber is adiabatic compression, and yields the exact result regardless of the size of discretization, in the absence of heat transfer and material flow in and out of the chamber. The detail of the derivation is given in the reference [1].

The predictor-corrector method is used for the state computation. The Runge-Kutta method can also be used, but the former was chosen because of its ability to detect computational problems when the iteration does not converge.

2.1.2 Plenum

The plenum object is a chamber with either constant volume or constant pressure. The constant volume plenum is used for the modeling of plenums and mufflers. The constant pressure plenum is used as a refrigerant source connected to the intake plenum or a refrigerant sink connected to the discharge plenum.

2.2 Passages

A passage object connects two chambers, and transfers the refrigerant between chambers. The amount transferred depends on the state of the two chambers and in some cases the internal state of the passage object itself.

2.2.1 Valve

A valve determines the amount of mass transfer based on the states of the two chambers that the valve connects, and the flow area which is computed from its lift. The valve object also computes and maintains its own state, such as the lift. The simplest model used is that of a mass-less spring, whose lift is solely determined by the pressure difference between the two chambers. The most critical valves are modeled as a mass-and-spring system with one degree of freedom, with additional enhancement to account for forward and backward sticktions, the reduction in dynamic pressure due to flow, and back leakage. While analyses with higher degrees of freedom are necessary to address such issues as internal stress and durability, one degree of freedom is quite adequate for most thermodynamic analyses[4]. The back leakage is modeled as the flow through a narrow gap whose height is an exponentially decreasing function of the pressure difference [5].

2.2.2 Orifice and Leak

The mass flow through an Orifice is determined by simple conservation of energy. The speed of exiting refrigerant flow is computed assuming that the upstream refrigerant undergoes isentropic pressure loss, but never exceeding the acoustic speed. This object is used when the flow cross-section is large enough so that the frictional losses can be ignored.

The flow rate through the Leak object can be computed using the Fanno flow model which incorporates choking . Choking may take place when the pressure difference is large. More detailed description of this model is given in the reference[1]. This model requires a large amount of computation time to develop. An alternative and effective way to assess the mass flow rate is to assume incompressible flow in the gap [6], with the correction to hold the maximum flow speed at the exit to be the acoustic speed.

2.3 Generalized Pistons

A generalized piston is an entity that causes the compression chamber volume to change and bear the mechanical and frictional load. In most applications, it is associated with Leak object.

3. IMPLEMENTATION AND EXAMPLES

A typical simulation code will have the structure shown as a pseudo-code in Table1. As stated earlier, the code is composed of initial input, component declaration, component connection, and computation loops.

3.1. Reciprocal Compressor

This is the case where the advantage of the object-oriented coding is least manifested, since the topology or connection relation among the components does not change. Yet, the object oriented approach allows easy replacement of the component object when the better model is constructed, and the design of the simulation code itself is greatly simplified. The components of a reciprocal compressor are shown in Figure 1.

3.2. Rotary Vane Compressor

The schematic and component drawings are shown in Figures 2a and 2b. Here, the chamber creation and removal events are driven by Vane (which is a specific implementation of a Generalized Piston), while the merger events are taken care of by chambers themselves. A vane object creates a trailing chamber object as it emerges out of the contact patch, and annihilates the preceding chamber as it enters the contact patch. The chamber, upon creation, merges itself with the suction plenum. It will separate itself from the suction plenum when it reaches the "end of suction" position. The instructions to connect and disconnect the passages, such as leaks associated with Vane are also included.

3.3. Scroll Compressor

The component drawing for a scroll compressor is shown in Figure 3. Here, the events are driven by the global clock for the entire compressor which keeps track of the global angular position. At angle 0, a new scroll segment and a crescent chamber which lies outside of the new scroll are created. The new chamber is merged to the suction plenum as it is created. The new chamber separates itself from the suction plenum when it reaches 2π radian. When the chamber approaches close enough to the central chamber, it is merged to the central chamber, and typically within 0.5π radian of the merger, it annihilates itself. The scroll, which is a specific case of a generalized piston, will follow a similar life cycle.

4. COMPARISON WITH EXPERIMENTAL RESULTS

An example of pressure profile from a CO_2 reciprocal compressor under development is shown in Figure 4. While both the intake and discharge valves are modeled to have a single degree of freedom, the discharge valve is further enhanced with sticktion and damping. The major features of the pressure behavior are well captured.

The pressure profile from a rotary vane compressor simulation is shown with the experimental measurement in Figure 5. The discharge valve is modeled to have a single degree of freedom with sticktion. The pressure profile from the simulation is in a very good agreement with the experiment. The dynamic feature of pressure variation due to the valve oscillation is captured quite well, except for being in the wrong phase.

The volumetric and thermal efficiencies of a scroll compressor are shown in Figure 6 as a function of compressor speed, along with the experimental measurements. In this graph, the operating speed should not be interpreted as a controlled independent variable, but rather as a number to distinguish the tested and simulated

operating conditions, since each of the operating conditions has a different compressor speed, intake state and discharge pressure.

5. CONCLUSION

The object oriented approach allows a compressor simulation code to be written in a natural and efficient way, particularly for compressors where the creation and removal of components occur in normal operation. This approach also allows easy development of simulation of different types of compressors as well as easy improvement once the base class objects are established.

The computational results are quite favorable compared to the measured performance data of actual compressors.

ACKNOWLEDGEMENT

The author wishes to thank the R&D Center of Zexel Corp., Compressor Design group, Advanced Compressor Development group and M1(Scroll) Compressor Design Group at the Kohnan facility of Zexel Corp., and Engineering Group at the Decatur, Illinois facility of Zexel USA Corp., for valuable discussions and experimental data.

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Table 1. Listing of pseudo-code representing the general simulation scheme

```
Input via menu
Initialize Chambers and form the linked list
Initialize the Barriers and form the linked lists
Initialize the Flows, form the linked list, and connect the chambers
for( ; ; ){
        Advance the Barrier link
        Advance the Chamber link
        Handle events such as creation, removal, merger, and connectivity change
        Flow Predictor
        Chamber Predictor
        while (not convergent){
                Flow Corrector
                Chamber Corrector
                Convergence Check
        }
        Compute and display required outputs
}
```

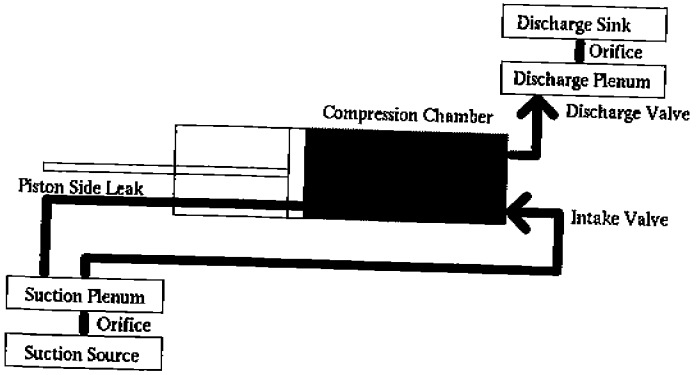

Figure 1. Object Diagram for Reciprocal Compressor

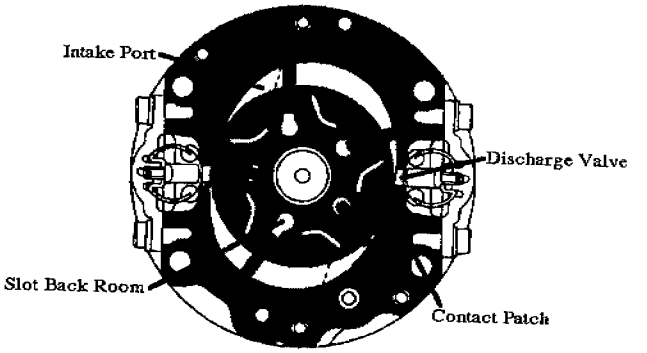

Figure 2a. Cross-section of a Rotary Compressor

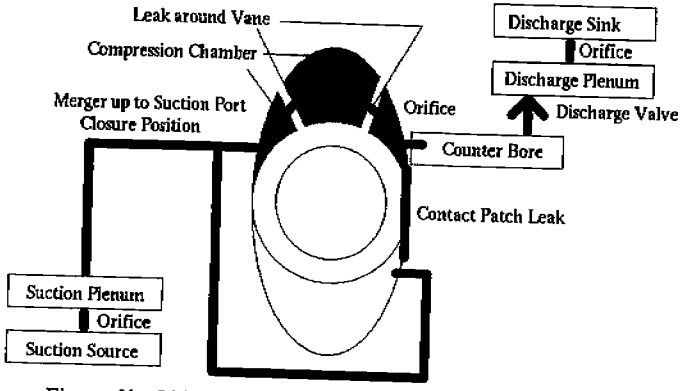

Figure 2b. Object Diagram for Rotary Vane Compressor

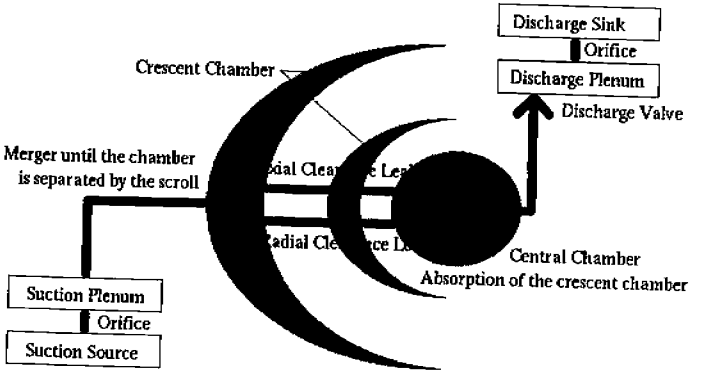

Figure 3. Object Diagram for Scroll Compressor

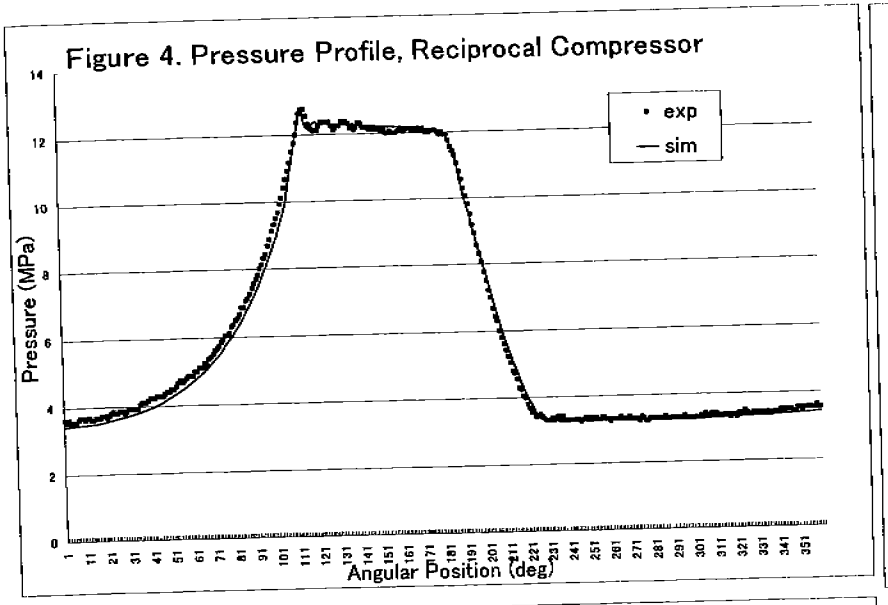
Figure 4. Pressure Profile, Reciprocal Compressor
Pressure (MPa)
Angular Position (deg)
exp
sim

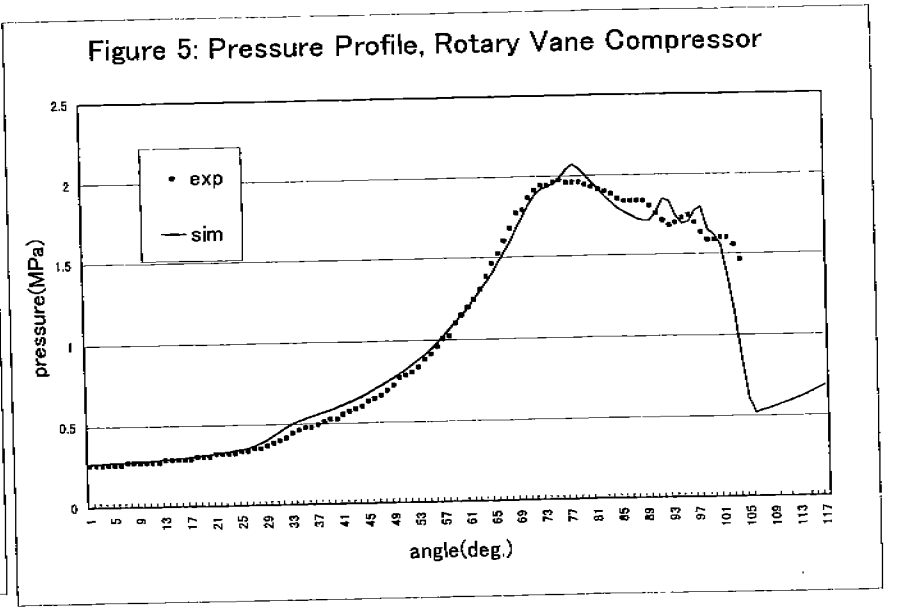
Figure 5: Pressure Profile, Rotary Vane Compressor
pressure(MPa)
angle(deg.)
exp
sim

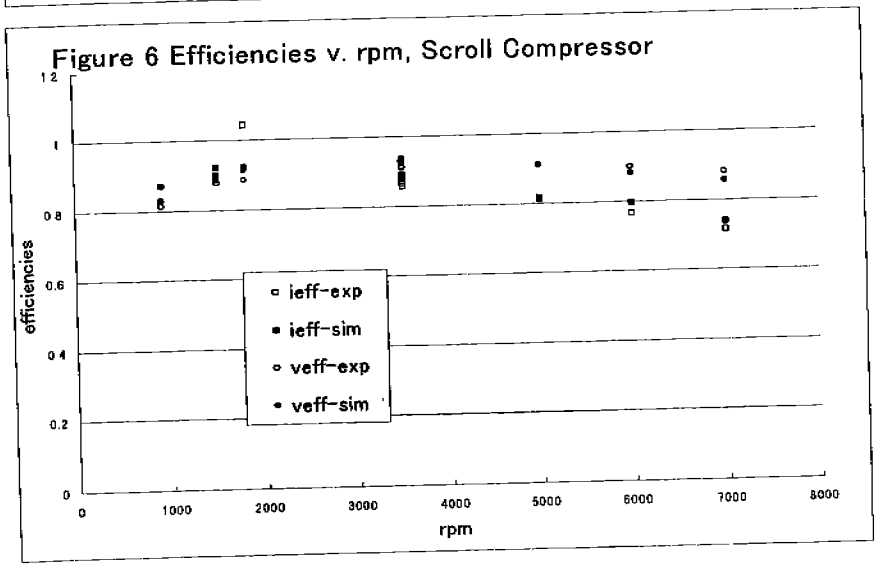
Figure 6 Efficiencies v. rpm, Scroll Compressor
efficiencies
rpm
ieff-exp
ieff-sim
veff-exp
veff-sim